4th ARMS 2006 – C.F. Leung, Y.X. Zhou (eds)
“Rock Mechanics in Underground Construction”, Singapore 2006, ISBN: 981-270-437-X, World Scientific

THREE DIMENSIONAL MODELLING OF A TUNNEL CAVE-IN AND SPILING BOLT SUPPORT

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Two issues related to a serious cave-in tunnel are discussed in this paper, namely rockmass parameter study and modelling for spiling bolts. In the first issue, best fitting the Hoek-Brown material does not give proper results. Therefore the cohesion and friction angle of the rockmass are obtained in another way, so that the models are able to reflect the true picture of the deformation. After this parameter study, the models are able to indicate the cave-in, the roof instability and the sinkhole. In the second issue, the spiling bolts are modelled by using pile element in FLAC3D. With this type of element, the loading condition, deformation and the effectiveness of a spiling bolt are well described. The “umbrella” effect and the important role of the bolt end fixing are also indicated.

Keywords: weakness zone, cave-in, sinkhole, FLAC3D, pile element, spiling bolts.

1. Background

1.1. *Cave-in Problem*

A serious cave-in problem was encountered in the headrace tunnel of Buon Kuop hydropower project, which is located at the centre part of Vietnam. The longitudinal section and location of the cave-in is presented in Figure 1.

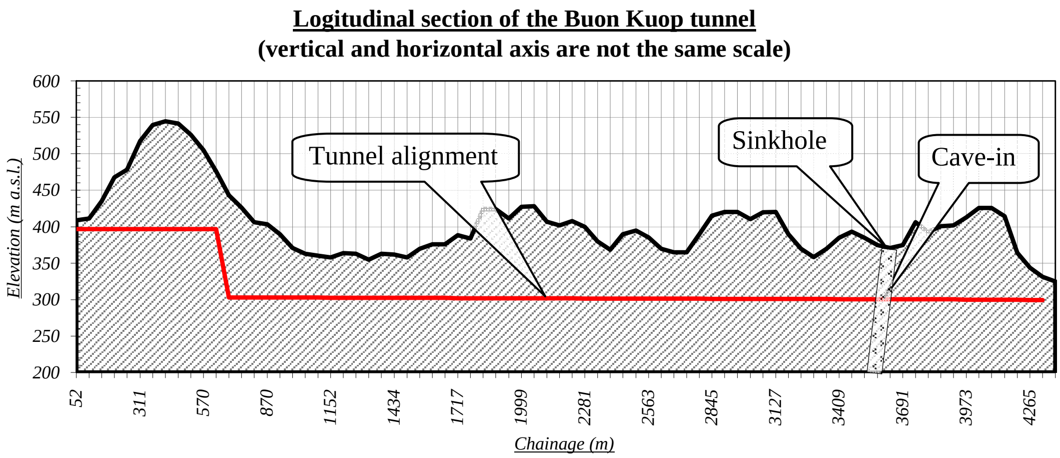

Figure 1: Water conveyance system of Buon Kuop project (PECC2, 2004)

The headrace tunnel consists of two parallel tunnels with 9 m diameter each in young sedimentary rocks. The tunnels are excavated by normal drill and blast method and in different progress. The second tunnel face is about 70 to 100 m lagged behind the first one. Headrace tunnel length is about 4.8 km, and the excavation was carried through three accesses: from intake,

from downstream, and at the middle. The cave-in problem happened in the first headrace tunnel at chainage K34+70, where the excavation was progressing from downstream and hit a weakness zone (about 15-20 m wide). Because the drilling equipment was not capable of handling drill rods longer than 6 m, probe drilling was not included in the tunnelling procedure.

After the blasting, the filling material of the weakness zone flowed into the tunnel with water. The movement of the weakness zone material continued all the way 60 m up to the surface and created a sink hole, as shown in Figure 2. The location of the sink hole is indicated in Figure 1.

Figure 2: Cave-in (left) and sinkhole (right) (PECC2, 2004)

Special support measures and excavation method were applied to get through the weakness zone, including spiling bolts, steel ribs, shotcrete and partial face excavation. More details information of the cave-in problem can be found in Trinh (2006).

1.2. *Analyses*

The cave-in problem is analysed by a number of analyses including convergence confinement method (CC-method) and modelling in 2D and 3D. The CC-method was used not only to analyse the cave-in but also for studying rockmass properties. All of these analyses can be found in Trinh (2006).

The CC-method was used as a kind of back analysis due to its simplicity. In this method, different ways of obtaining rockmass properties in the weakness zone were tested, including:

- Fitting the *in situ* test for a similar material in investigation tunnel by Mohr-Coulomb criterion for c, ϕ, σ_{cm} and *in situ* test for E_m.
- Fitting the *in situ* test for a similar material in investigation tunnel by Hoek-Brown criterion for GSI, m_i, D and E_m, with σ_{ci} from laboratory tests.
- Studying the weakness zone rockmass and evaluating the corresponding GSI (Hoek-Brown criterion), with σ_{ci} from laboratory tests.

Outcomes from the analyses show that rockmass properties obtained by the last method and using the Hoek-Brown criterion give the most realistic results (Trinh, 2006). The obtained rockmass properties are presented in Table 1.

Table 1: Rockmass properties of the filling material

Hoek Brown Classification	Hoek Brown Criterion	Mohr Coulomb Fit	Rockmass Parameters
σ_{ci} =12 MPa	m_b = 0.2996	c =0.33MPa	$\sigma_{tension}$ = 0.00 MPa
GSI =25	s = 1e-004	ϕ =15.43°	σ_{cm} = 0.09 MPa
m_i =7	a = 0.53		σ_{cm2} = 0.74 MPa
D =0.3			E_m= 698 MPa
Note: Minor principle stress is assumed to be less than 4.0 MPa for fitting the MC criterion			

2. Parameter Studies

In addition to the convergence confinement method, the cave-in problem at the Buon Kuop weakness zone is analysed using a 3D-model. FLAC3D version 2.1 is used for the analyses. In this version the Hoek-Brown material is not available, so the Mohr-Coulomb material is used. The cohesion and friction angle of the Mohr-Coulomb material is obtained by fitting the equivalent Hoek-Brown material. Information about fitting technique can be found in Hoek et al (2002)

The purposes of the analyses are to observe the deformation of the tunnel in more detail in 3D. The 3D models are able to provide many details concerning the effectiveness of the support measures, and impact of excavation advance length and partial face excavation.

Before going into detailed analyses, the model should be simulated with the initial conditions. This simulation is for calibrating the model. This is also the reason for carrying out the parameter study.

2.1. *Simulation with Best Fit Rockmass Properties*

The obtained rockmass properties from convergence confinement method (see Table 1) are used for this simulation. Results of the simulation are presented in Figure 3.

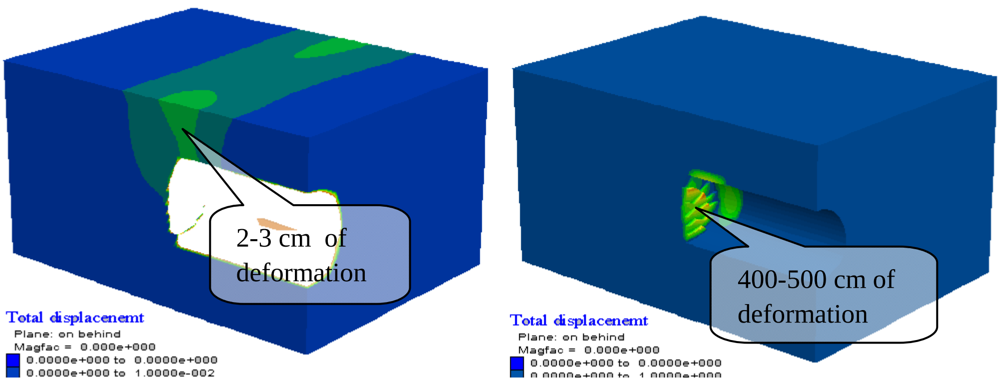

Figure 3: Deformation - full face excavation, no support, ground water level at 355 m a.s.l.

(Left: deformation less than 10 cm; Right: deformation less than 1000 cm)

Due to no groundwater measurement, it is assumed that the groundwater elevation is situated at 355 m a.s.l. This level is considered to be the original level of the groundwater and just about 5 m below the ground surface. Thus, a water head of 55 m is created above the roof of the tunnel.

The reason for this assumption is for checking if the model is able to reflect the true deformation in the first tunnel when it hit the weakness zone (cave-in, sinkhole).

The results show that extremely large deformation occurs at the tunnel face and at the part of the roof that is inside the weakness zone. The deformation is up to 400-500 cm. There is only 2-3 cm deformation developing upward in the weakness zone. The main reason for the large deformation in the model is groundwater. After excavation, original pore water pressure becomes zero at the tunnel face leading to the water pressure redistribution. The redistribution of the pore-pressure affects the total pressure and results in deformation, with the defined deformation modulus.

In the simulation, a significant part of the rockmass around the tunnel has failed, resulting in the simulation non-converging. The FLAC3D has limitation in dealing with large deformation, even though a “large deformation” option is provided. Due to the non-convergence, the calculated deformation should not be taken as the final value.

From the results, some comments can be made. The model is able to demonstrate the cave-in by an extremely large deformation at the tunnel face. However, the model does not show the sink hole which was there in reality. Large deformation in the model just develops around the tunnel face and a small upward deformation of about 2-3 cm is indicated. The model also failed to show the true deformation of the tunnel periphery in good rockmass area (in the model, this deformation is more than 10 cm which is too high).

The reason for not showing the sinkhole is that the material is Mohr-Coulomb. With its linear failure criterion together with too high cohesion, large deformation could not develop further into the rockmass to indicate the sinkhole. Thus, it can be concluded here that the rockmass properties of the model should be studied to obtain a more realistic model.

In best fit technique, the cohesion and friction angle are sensitive to the maximum minor principle stress (σ_3). The above maximum minor principle stress may be too high (4.0 MPa), therefore other values of σ_3 is selected ranging from 3.0 to 0.20 MPa. The corresponding cohesions and friction angles were obtained. Then these parameters were put into simulations. None of them give a reasonable result. The reason is that when the σ_3 is reduced, the cohesion is reduced but the friction angle is increased.

2.2. *Parameter Studies*

In this parameter study, new Mohr-Coulomb parameters are obtained not by fitting any range, but by lowering down the Mohr-Coulomb line to a reasonable level so that the cohesion and friction angle are both lowered. With lower cohesion and friction angle, the stress redistribution, and thus the deformation, can penetrate deeper into the rockmass. The initial criterion for choosing the mentioned line or parameters (c =0.05 MPa, ϕ = 21^o) is based on four conditions (i)low cohesion (ii) medium friction angle (iii)not

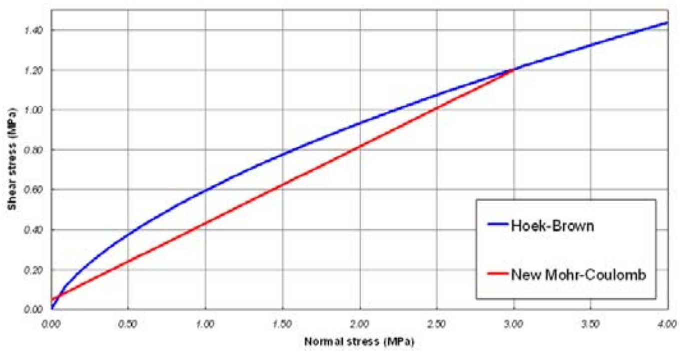

Figure 4: Mohr-Coulomb and Hoek-Brown criteria.

too far from the trend of the Hoek-Brown criterion and (iv) giving a qualitatively reasonable result. (see Figure 4).

New rock mass properties are put into the model for simulation. In this simulation, the ground water level is assumed to be at 309.5 m.a.s.l. The reason is to reduce the amount of the deformation so that the model should have better chances to converge. Results of the simulation are presented in Figure 5.

The results with new rockmass parameters clearly indicate the face and the roof instability by very large deformation (150 cm). Large deformation has also propagated deeper into the rock mass. This deformation is developed upward along the weakness zone such obviously indicating the sinkhole. The model now becomes more realistic for further detailed analyses.

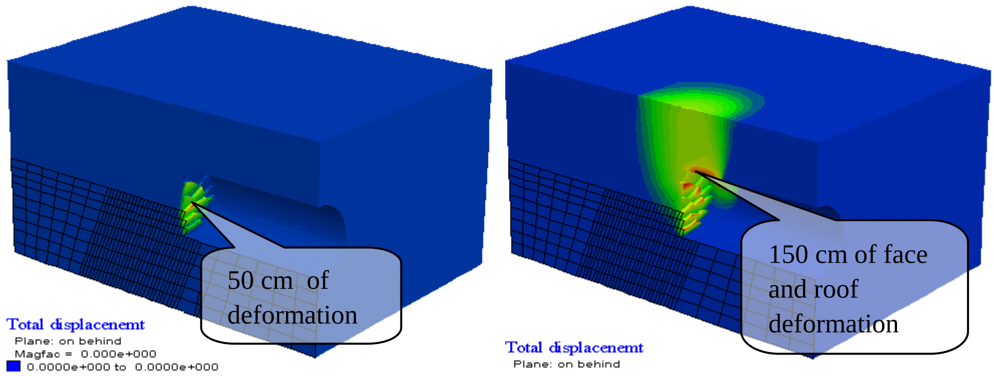

Figure 5: Deformation - full face excavation, no support, ground water level at 309.5 m a.s.l.

(Left: deformation with c =0.33 MPa, ϕ = 15.43°; Right: deformation with c =0.05 MPa, ϕ = 21°)

Similar works are done, and it is found that the cohesion can be from 0.05 to 0.07 MPa, and the friction angle can be from 21 to 27°. The lower cohesion should be corresponding to the higher friction angle. (Trinh, 2006)

3. Spiling Bolt Models

Spiling bolts are often used in tunnelling in extremely poor rock masses. Spiling bolts provide a safe protection ahead of the tunnel face. In spite of their effectiveness and commonly use, spiling bolts are not fully studied today. In this research, spiling bolts are studied in great detail.

3.1. *Model Selection for Spiling Bolts*

In FLAC3D, there are two types of elements that can be used to model a bolt. These are cable element and pile element. Normally, a radial bolt is often modelled by cable element, but this element may not be suited for a spiling bolt due to their differences.

Cable element: This element can be imagined as a long steel bar, which can only carry the axial tensile and axial compressive loads (Itasca, 2005). The element has no capability to carry bending moment. The bearing capacity of this type of element is achieved by the friction between the outer skin of the element and the rock mass and the strength of the element itself.

This type of element is suitable for modelling supports such as anchored cable bolts, radial rock bolts (end anchored or grouted), and pre-tensioned rock bolts. In those bolts, the load bearing is mainly axial.

Pile element: The main difference between cable element and pile element is that the pile element can carry other loads than axial loads. With pile element, loads such as normal to element axis or bending moment can be carried (Itasca, 2005). Pile elements can be used to model bolts that are subjected to complicated loading conditions such as a loading condition of both shear and tension. For example, anchored bolts to prevent the movement of two rock blocks in which bolts have to resist a shearing load and tension. Thus, pile elements can be used to model the spiling bolts because spiling bolts can also be classified as bolts that are working in complicated loading conditions. Spiling bolts are directed approximately parallel to the tunnel axis. Forces on the spiling bolts are friction along the bolts, and also forces acting normal to the bolt axis. The normal forces result in a bending moment in the bolts.

Load bearing capacity of a pile element is provided by the skin friction between the element and rock mass, the strength of the element, the stiffness of the element, and the cross section shape of the element (circular, rectangular, ring).

In this research, pile element is selected to model the spiling bolts for tunnelling support at the Buon Kuop weakness zone.

3.2. *Simulation for Spiling Bolts*

When using pile element to model spiling bolts 13 input parameters are required to define mechanical properties of the bolts (see Table 2). In Table 2, parameters from 1 to 8 can be calculated or obtained without too much effort. The remaining parameters are not easy to define. It may require *in situ* tests to find the true values. In this research, due to limitation of time and finances, *in situ* tests were not carried out. The reference is made to Itasca examples to obtain the values.

Table 2: Bolt properties using pile element

No.	Properties	Unit	Value
1	Young's modulus of the bolts (steel) E	*MPa*	200.10^{3}
2	Poisson's ratio of the bolts (steel) ν		0.25
3	Cross sectional area of the bolts s (D_{out} = 50 mm, D_{in} = 46 mm)	m^2	3.10^{-4}
4	Perimeter of the bolts p (bolt length = 6 m)	*m*	0.16
5	Ultimate tensile strength t	*MN*	0.136
6	Second moment, respect to y-axis of the pile element I_y	m^4	44.10^{-9}
7	Second moment, respect to y-axis of the pile element I_z	m^4	44.10^{-9}
8	Polar moment of inertia J	m^4	87.10^{-9}
9	Shear coupling spring cohesion per unit length	*MN/m*	0
10	Shear coupling spring stiffness per unit length	MN/m^2	10
11	Normal coupling spring cohesion per unit length	*MN/m*	150
12	Normal coupling spring stiffness per unit length	MN/m^2	1000
13	Shear coupling spring friction angle ϕ	*degree*	20

At the Buon Kuop tunnel, spiling bolts are installed along the roof of the tunnel with a bolt spacing of 30 cm. Bolts are installed after every second excavation round, so the bolts row spacing is 2 m.

Results of bolts deformation and the axial force and bending momentum in the bolts are presented in Figure 6. The results showed large deformations and forces are located at the bolt ends near to the tunnel periphery. This suggests that the bolt ends should be properly supported to improve the effectiveness of spiling bolts. In reality, the spiling bolt ends are often supported by radial bolts, steel ribs or concrete. More information can be found in Hoek (2000), for example.

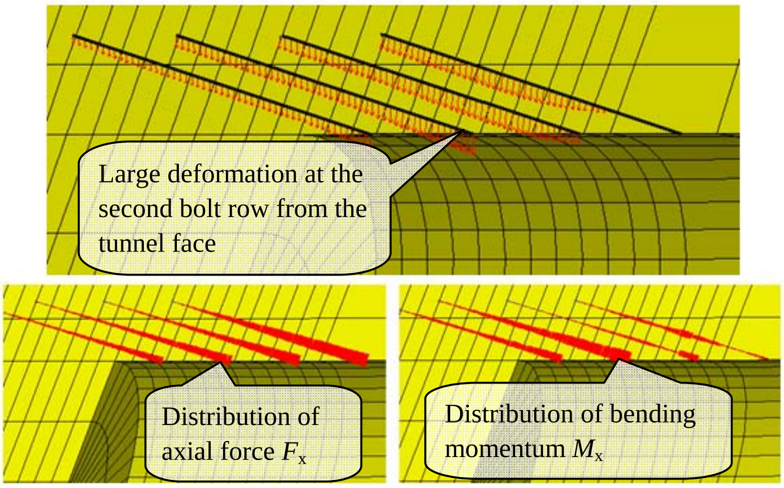

Figure 6: Deformation and forces acting on spiling bolts

With bolt ends are fixed, the model showed a great reduction of the deformation ahead of the tunnel, as shown in Figure 7. As can be seen from the picture, by providing the “bolt ends fix”, the spiling bolt system becomes stiffer to some extent beyond the tunnel face, which creates an “umbrella” to protect the next excavation. This effect together with the interaction between bolts and rock mass are probably the fundamental bases for using spiling bolts as a pre-support measure. The “bolt ends fix” can be done by providing radial bolts, steel ribs or concrete arch.

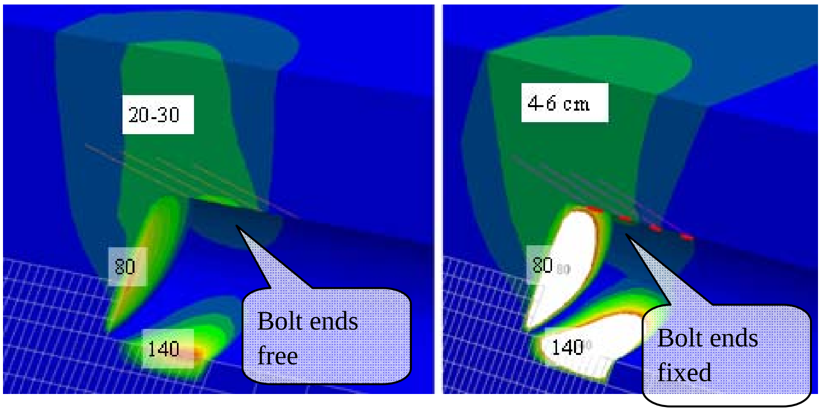

Figure 7: Reduction of the deformation when fixing bolt ends

Bending momentum distributed along the spiling bolts may suggest that the stiffness of the bolts is very important for their performance. From this point of view, too long spiling bolts are not recommended because the stiffness of the bolts will be reduced when increasing bolt length. The appropriate length of spiling bolts may be defined by numerical models as above with different bolt length. However, model with common spiling bolt length of 6 m showed a very effective result. When these bolts are properly fixed, the deformation on roof and ahead of the tunnel is significantly reduced from 20-30 cm down to 4-6 cm. Therefore, spiling bolts longer than 6 m may not be necessary.

4. Concluding Remarks

The first and very important remark is that there was no Hoek-Brown material in the FLAC3D version 2.10. This limitation had great effect on reducing the reliability of the result. Back analysis showed that the models, using Mohr-Coulomb criterion with best fit rockmass properties, failed to describe what happened at the Buon Kuop weakness zone (sinkhole and roof instability).

The authors will not recommend using FLAC3D-version 2.10 with best fit data for the Buon Kuop weakness zone. It may lead an inexperienced engineer to a completely wrong decision, especially when it is carried out without any good reference for back analyses. If such 3D analyses (using Mohr-Coulomb criterion and best fit rockmass properties) are carried out before the excavation, where there is no information about deformation for back analyses, then based on the results one may conclude that there will be no problems in the roof of the tunnel but only at the face. The results from models actually turn the attention of engineers from the roof to the wrong location – the tunnel face. This may lead to serious problems.

To avoid such serious mistakes, the method should only be used together with other codes for cross checking (such as Phase2) or with a comprehensive parameter study as it was performed.

A quick check of the model with FLAC3D- version 3.0, where the Hoek-Brown material is available, showed that the rockmass properties given in Table 1 gave reasonable results.

With pile element in FLAC3D, one can have a full picture of how spiling bolts work such as the friction between the bolts and rock mass, the contribution of the stiffness of the bolts to control deformation and the “umbrella” effect of the bolts. It can be seen from the models that the pile elements are better than cable elements in describing the working condition of spiling bolts. This useful information is provided in great detail from the 3D simulations. However, *in situ* tests and numerical models should be made to obtain more accurate values of the mentioned spiling bolt properties.

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